Coherent spatiotemporal control of light through a multiply scattering medium

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Abstract

We report broadband characterization of the propagation of light through a multiply scattering medium by means of its Multi-Spectral Transmission Matrix. Using a single spatial light modulator, our approach enables the full control of both spatial and spectral properties of an ultrashort pulse transmitted through the medium. We demonstrate spatiotemporal focusing of the pulse at any arbitrary position and time with any desired spectral shape. Our approach opens new perspectives for fundamental studies of light-matter interaction in disordered media, and has potential applications in coherent control and imaging.

Introduction

Propagation of coherent light through a scattering medium produces a speckle pattern at the output [1], due to light scrambling by multiple scattering events. Both phase and amplitude information of the light are spatially mixed, thus limiting resolution, depth and contrast of most optical imaging techniques. Over the last past years, wavefront shaping techniques have revolutionized the control of optical waves in disordered media, exploiting the fact that the scattering process is deterministic. With more than a million available degrees of freedom, spatial light modulators (SLMs) allow to manipulate the propagation of coherent light, using different techniques [2, 3].

With an ultrashort laser, photons exit the scattering medium at different times, giving rise to a broadened pulse at the output. Temporal spreading of the original pulse is characterized by a confinement time that can be order of magnitude longer than the initial pulse duration. Therefore, applications that require an ultrashort pulse, such as multiphotonic imaging and non-linear physics are rapidly out of reach in a multiply scattering system. With a single SLM, one can manipulate spatial degrees of freedom to adjust the delay between different optical paths. Therefore spatial and temporal distortions can be both compensated using wavefront shaping techniques, for example to perform spatiotemporal focusing [4–6].

Here, we present the Multi Spectral Transmission Matrix (MSTM), an extension of the Transmission Matrix approach in the spectral domain, to fully control, both spatially and spectrally, the propagation of an ultrashort pulse in a disordered medium. The MSTM coefficients include the relative phase relation between the different frequencies of the pulse, which is essential for the temporal control of the output pulse [7]. We demonstrate deterministic spatiotem- poral focusing and enhanced excitation of a non-linear process, as well as the deterministic achievement of a variety of temporal profiles, that could not be directly reached previously [8].

Experimental results

The number of monochromatic transmission matrix to be measured to fully describe the propagation of the broadband signal is the number of spectral degrees of freedom, in essence the ratio between the spectral bandwidth of the ultrashort pulse and the spectral correlation bandwidth of the medium [8]. The latter expresses the difference in input frequency needed to obtain two uncorrelated speckle pattern. The MSTM is experimentally measured, using a Ti:Saph laser source producing tunable cw light and 110 fs ultrashort pulse. A phase-only SLM modulates the wavefront. The scattering sample is a thick layer of ZnO nanoparticles randomly distributed.

We are using two different methods to demonstrate spatiotemporal control of the output pulse. Firstly, we excite a non-linear process, two-photon fluorescence, that allows to differentiate the spatial from the spatiotemporal focusing.

The fluorescent sample is a powder of fluorescein diluted in ethanol. The second method is an interferometric cross correlation between an ultrashort pulse and the output pulse of the scattering medium.

Fig 1 shows the main experimental results. We can deterministically temporally compress the pulse close to its initial time-width by imposing a flat phase relation between the different frequency components of the output pulse. Spatial focusing is achievable by focusing only one frequency of the output pulse. The MSTM gives also access to a more sophisticated spectral shape, as the spectral phase relation is known. For example, Fig 1 illustrates spectral shaping of the output pulse, by shifting the arrival time of the pulse with a controllable delay, creating a dip inside the pulse, or generating two pulses with a controlled delay.

Any temporal shape is in principle possible, with a resolution given by the temporal duration of the pulse, over a temporal interval related to the confinement time of the medium, using only spatial degrees of freedom of a single SLM. This full spatiotemporal control of the output pulse opens interesting perspectives for the study of light-matter interaction and for non-linear imaging in multiply scattering media.

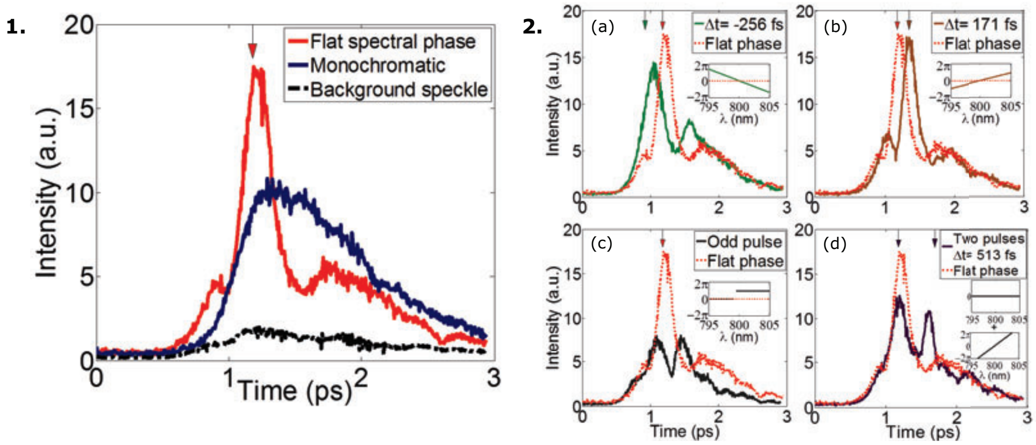

Fig. 1. Spatiotemporal control of an ultrashort pulse after propagation through the scattering sample. (1) Spatial and spatiotemporal focusing at a given time and at a given position are deterministically achievable. (2) Any spectral shape can be obtained. See main text.

References

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